US Dept of Defense Explosives Safety Board
1998 Explosives Safety Seminar Orlando, Florida – August 18 – 20, 1998
Explosion Effects Containment Session

Shrapnel Impact Probability Analysis Computer Code Development And Diagnostic Port Failure Analysis For LLNL's Explosives Testing Contained Firing Facility (CFF)

David E. Price[1], Bob Spence [2], Russell Towle [3]
Lawrence Livermore National Laboratory
P.O. Box 808 L-379
Livermore, CA 94550
(925) 422-3980
price16@llnl.gov, B.Spence@mailbox.uq.edu.au, rustybel@foothill.net

Introduction

Lawrence Livermore National Laboratory's (LLNL) Contained Firing Facility (CFF) is a facility to be constructed for explosives testing of up to 60 kg of cased explosives at LLNL's Site 300 Explosives Test Site. The CFF will be a large, rectangular, reinforced concrete firing chamber, lined with steel for shrapnel protection. The CFF will contain several glass ports for cameras, lasers, and other diagnostic equipment to be used for data collection during planned explosives detonations. Glass is used due to the need for the greatest possible optical clarity. This computer code and the associated study were developed during the CFF final design stage to determine probabilities and consequences (bounding and best estimate) of impact of shrapnel, due to concerns about the possible effects of rebounding shrapnel on these glass diagnostic ports.

Inquiries and searches discovered no established methodology for doing quantitative shrapnel impact probability analyses. Discussions with programmers in the three-dimensional graphics community led to the conclusion that ray-tracing software could be adapted to do the analysis. So the decision was made to develop the computerized tools needed to do shrapnel impact probability analysis.

The analysis approach was developed by the team as a whole. David E. Price (a Senior Safety Analyst with Onsite Engineering & Management, a sub-contractor at LLNL) led the team. Bob Spence (an independent consultant and developer supporting both Macintosh and Windows platforms, with a strong preference for the Macintosh, and with a particular interest in graphics/animation/image processing applications) developed the computer code algorithms and modified the POV-Ray code. Russell Towle (of Giant Gap Press, a geometer and writer who

---

[1] Onsite Engineering & Management
[2] Independent Consultant
[3] Independent Consultant, Giant Gap Press

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **AUG 1998**	2. REPORT TYPE	3. DATES COVERED **00-00-1998 to 00-00-1998**

4. TITLE AND SUBTITLE **Shrapnel Impact Probability Analysis Computer Code Development And Diagnostic Port Failure Analysis For LLNL's Explosives Testing Contained Firing Facility (CFF)**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Lawrence Livermore National Laboratory,P.O. Box 808 L-379,Livermore,CA,94550**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001002. Proceedings of the Twenty-Eighth DoD Explosives Safety Seminar Held in Orlando, FL on 18-20 August 1998.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

uses Mathematica to investigate close-packings of polyhedra, and often animates polyhedral models using POV-Ray) developed the 3-D model of the facility.

We developed a customized version of the Persistence of Vision™ Ray-Tracer (POV-Ray™) version 3.02 code for the Macintosh™ Operating System (MacOS™). POV-Ray creates three-dimensional, very high quality (photo-realistic) images with realistic reflections, shading, textures, perspective, and other effects using a rendering technique called ray-tracing. It reads a text file that describes the objects and lighting in a scene and generates an image of that scene from the viewpoint of a camera, also described in the text file. More information about POV-Ray, including the executables and source code, may be found at <http://www.povray.org>.

The customized code (POV-Ray Ricochet Tracker, V3.02 – Custom Build) generates fragment trajectory paths at user designated angle intervals in three dimensions, tracks these trajectory paths through any complex three-dimensional space, and outputs detailed data for each fragment path as requested by the user, including trajectory source location, initial direction of each trajectory, vector data for each surface/trajectory interaction, and any impacts with designated model target surfaces during any trajectory segment (direct path or reflected paths). This allows determination of the three-dimensional trajectory of each simulated fragment, as well as overall and individual fragment probabilities of impact with any designated target(s) in the three-dimensional model. It also allows identification of any areas of particular concern due to grouping (in discrete areas) of fragment paths that lead to hits on the target areas of concern.

The default code output includes data for specified fragment paths up through four reflections, with the number of target hits for each path segment listed. Output is grouped by target number, arbitrarily assigned in order as the target objects are declared in the input model text file. Hits on the targets are listed by path segments (e.g., direct path, one bounce, two bounces, etc.).

The code has the capability to output a separate data file containing full x, y, and z directional data for each fragment path, to output just the data for a user specified number of reflections, or to output data for just the paths that lead to hits on the specified targets.

The code assumes that the shrapnel originates from a point source located at the defined camera position in the model. The shrapnel pieces are assumed to be ideal, spherical, point-sized objects. Travel paths are assumed to be short and at high speed, i.e., gravitational curvature of the shrapnel paths is ignored. Reflections are assumed to be ideal, i.e., the reflection angle is equal to the incident angle.

Both irregular fragment shapes and rotational momentum of the fragments would be expected to cause individual fragments to deviate from the ideal fragment paths. However, the aggregate real-world fragment paths would not be expected to significantly deviate from the ideal paths because of the averaging out of the deviations. Any collisions or other interactions between fragments are ignored. The analysis code has the capability to simulate non-ideal reflections caused by irregular fragment shapes by introducing either regular or random surface roughness or bumpiness. However, no simulation method available in the analysis code has been identified to simulate the effects of rotational energy.

Impact Probability Analysis

Performing the Impact Probability Analysis

The three-dimensional CFF facility model developed for this analysis included a 55 ft. x 51 ft. x 30 ft. room, a 41 ft. x 14 ft. x 2.5 ft. high raised area around the camera floor ports with 45 degree beveled edges on one side and one end, a blunted pyramid shaped x-ray bullnose on one end, and shrapnel shields for all 13 floor ports and for 3 wall ports. Shields are expected to be present on only a few active wall and floor ports during operational detonations, with the others blanked off. An Internet web page at http://www.llnl.gov/str/Baker.html shows a 3-D illustration of the CFF and gives more background on the facility.

Analysis code runs were performed on a Power Macintosh 6100/66 and on a Power Macintosh 8100/110, both using MacOS 8.0. Run times varied from a few minutes to more than 15 hours due to the different input and output options utilized.

Code runs were done for shot placement in the center of the room and also for eight other shot placement positions to ensure that the worst case number of impacts on the ports was evaluated. Runs were performed to generate hit frequency data, to generate fragment path data, and to render pictures of the fragment paths in the model for model verification and visualization purposes. Code runs were done at several angular resolutions to determine the optimum resolution to ensure that all significant fragment paths were identified. There were significant changes in hit probabilities between 0.5 and 0.3 degree spacing but no significant changes between 0.3 and 0.1 degrees. Final analysis runs for the selected shot placements were done at 0.1 degree spacing. This gave 4,126,180 fragments, with initial fragment paths distributed evenly around the source.

Impact Probability Analysis Results

In the hit data output files, the angles of impact with the ports were binned into 10 degree groups to give an idea of the angular grouping of the highest frequency fragment paths. Each output file includes:

- The input file name (with a designator of ".pov")
- Trace level (total number of fragment path segments analyzed per fragment)
- Trajectory spacing (resolution) in degrees
- The number of fragments simulated (designated by "Trajectories:")
- Shot location (Origin)
- Hit statistics, which include an object designator (sequentially from 0) and hit statistics for each path segment, from direct (0 bounces) through 4 bounces. The first line is a summary for the specific target, followed by 9 lines of data for each angle grouping (0-10 degrees to 80-90 degrees)

Fragment path trace output files include:

- Ray origin directional data in two forms: altitude (where an angle of 90 corresponds to a direction along the vector from the origin toward the "look_at" position in the camera

declaration) and azimuth (the angle around the altitude); and direction vectors (x, y, and z cosine data for the direction of the fragment path).

- x, y, and z coordinates of the surface hit by the direct fragment path
- x, y, and z coordinates of the surface(s) hit by the reflected fragment (reflected ray segments), up through as many as four bounces
- Any targets hit by the fragment (designated by a label of '(Object #)' after the x, y, z coordinate data)

Figure 1 shows a POV-Ray Ricochet Tracker rendering of the one and two bounce fragment paths for hits on port 3 for a central shot placement. One bounce hit paths are in yellow, two bounce hit paths are in magenta (these will both be gray or black in copies of the report), and the fragment path's shadows are black. Note that although the port shield roofs were modeled in the computer analysis runs, they were removed for rendering these pictures so that the fragment paths into the ports would be more visible. This visual display of the analysis results identified three areas of grouping of shrapnel paths that led to hits on the diagnostic ports.

The complete data set for a 1.0 degree resolution run was 3375 pages. A complete data set for a 0.1 degree resolution analysis would be approximately 500,000 pages.

Probabilities of hitting the ports were estimated by dividing the number of predicted hits on the worst case port for each path segment (direct, one bounce, two bounces) by the total number of fragment paths modeled for the entire facility per shot (4,126,180). This gives a probability of hitting the worst case port per fragment per path segment. These probabilities were then combined to get the overall worst case probability of hitting the worst case port for that particular shot location, summarized in Table 1. The bounding probabilities of hitting any specific diagnostic port – as predicted by this analysis – are relatively low (4.5 E-5 per shot). The overall probability of hitting any port would increase as the number of exposed ports increases.

Table 1 Port Glass Estimated Impact Probabilities (Examples)

Shot Location	**Direct path** **Probability**	**One bounce** **Port ID/Hits/ Probability**	**Two bounces** **Port ID/Hits/ Probability**	**Overall Probability**
CFF Center	0	3-FP/29 7.0 E-6	4-FP/101 2.4 E-5	3.1 E-5
North Center	0	1-FP/46 1.1 E-5	**1-FP/139** **3.4 E-5**	**4.5 E-5**

Impact Effects Analysis

The second part of the study was to estimate the probabilities that impacts on any one of the ports after one or two bounces from any of the surfaces in the facility would cause the glass port to fail. Due to energy loss during the interactions with the metal surfaces in the CFF facility, the fragments would not be expected to have enough energy left to breach a glass port after three or

more bounces. The computer code analysis was combined with empirical predictions from TM-5-1300, “Structures To Resist The Effects Of Accidental Explosions”[1], and data from other sources to estimate the frequency of failure of the glass diagnostic ports.

Quantitative analysis of the failure probabilities was not possible due to a lack of verifiable data. Even though the following includes numbers for these probabilities, these numbers should be viewed as judgments, not as hard and fast numbers. The information below is a brief summary.

Fragment Considerations

Shrapnel sizes and velocities are dependent on the specific dimensions and quantities of both explosives and materials present in an explosives assembly. An LLNL study[2] documented several parameter calculations important to the study of shrapnel effects for a maximum weight steel cased explosives test for the CFF using methodology from TM 5-1300 [DOD 1990]. Other parameters were calculated in this analysis. The report notes that the calculated results are in general agreement with experimental results, which would be expected since the formulas in TM-5-1300 are empirically derived.

Several factors affect the energy the fragments may potentially transfer to the diagnostic ports. Velocity is decreased by the flight through the air due to aerodynamic drag. Energy is lost when the fragment bounces off of (and interacts with) the various surfaces in inelastic collisions, with a substantial fraction of the energy causing deformation of the steel surfaces[3] (assumed 75% bounding, 90% average).

Fragment Impact Effects

The Security Glass Specification Guide[4] for Laminated Security Products/All Glass and Attack Resistant Security Systems[5] list requirement for fragment resisting characteristics of laminated windows from UL 752. Their 2 inch laminated glass bullet-resistant windows resist breakage from a high powered 30-06 rifle bullet of 220 grains (0.5 ounces) traveling at 2410 feet per second. This corresponds to a kinetic energy of 4 kilojoules. This is similar in energy, speed, mass, and glass thickness to the parameters of interest in this study.

Southwest Research Institute performed testing of annealed glass windows to determine fragment resistance for a turbine testing facility[6]. This testing documented energy and penetration depth for two fragment weights and speeds (.27 lb. at 750 ft/sec and 3.81 lb. at 585 ft/sec). A comparison was done between these test results and the range of fragments calculated for CFF.

Using methodology from TM 5-1300, CFF maximum fragment velocity was calculated to be 5554 ft/sec (1693 meters/sec). Average fragment mass is 1.1 ounces (0.033 kg). The total number of fragments produced is 3934. The number of fragments this size or larger is 956. The 95% confidence level (CL) fragment mass is 4.93 ounces (0.15 kg). The number of fragments this size or larger is 197. The design fragment mass is 9.8 ounces (0.29 kg). The number of fragments this size or larger is 57 (1.4%). The design fragment mass of 9.8 ounces is about the same as a 98.5% confidence level fragment mass.

At the initial velocity of 5554 ft/sec (1693 m/sec) the fragments have the following energies: Average fragment, 47 kilojoules; 95% CL fragment, 211 kilojoules; Design fragment, 421 kilojoules. Strength of the glass ports was based upon two inch glass.

Best estimate probability of an average weight fragment breaching a port glass = <1 E-6 per shot.

Best estimate probability of a design fragment breaching a port glass = 1.8 E-3 per shot. Best estimate probability of a design fragment breaching both port glasses = <1 E-6 per shot

Bounding probability of an average weight fragment breaching a port glass = 1.1 E-2 per shot. Bounding probability of an average weight fragment breaching both port glasses = <1 E-6 per shot

Bounding probability of a design weight fragment breaching a port glass = 2.6 E-3 per shot. Bounding probability of a design weight fragment breaching both glasses port = 6.8 E-4 per shot

None of the fragments of concern are expected to have enough energy to breach two pieces of glass after two or more bounces, either for the bounding case or for the best estimate case.

Conclusions

It is concluded that the best estimate probability of breaching any one port glass is 1.4 E-3 per shot, and that the bounding probability of breaching any one port glass is 1.1 E-2 per shot.

It is concluded that the best estimate probability of breaching both glasses in a port is <1 E-6 per shot, and the bounding probability of breaching both glasses in a port is 6.8 E-4 per shot.

As a result of this and a concurrent pressure effects analysis, thicker glass was chosen for the second glass in each port. Also, a pressure/fragment resistant wall will be installed between the diagnostic rooms and the control room. Personnel will be prohibited from occupying either the camera room or a diagnostics room during test shots.

The POV-Ray Ricochet Tracker computer code may be used for shrapnel or bullet ricochet analysis in any desired short-range setting, outdoors or indoors, by modeling the specific facility.

Output File Examples

Default File Output

```
File CFF NC .1_9
Trace level    5
Nominal trajectory spacing (degrees)    0.100000
Total trajectories       4126180.000000
Origin(x,y,z)  -2.920000 6.630000  4.000000
Object  0 0    46   139  251  247
0.0-10.0  0    0    0    0    0
10.0-20.0 0    0    0    53   11
20.0-30.0 0    0    9    29   59
30.0-40.0 0    13   62   91   90
40.0-50.0 0    17   38   44   34
50.0-60.0 0    0    23   14   17
60.0-70.0 0    16   7    20   36
70.0-80.0 0    0    0    0    0
80.0-90.0 0    0    0    0    0
```

User Requested Path Data File Output

```
Ray start: alt = 47.300000, azimuth = 117.641279, Dir vector =
<-0.734915, -0.314622, 0.600761>
hit at (x,y,z) -27.109906,-11.605922,26.161180
hit at (x,y,z) -7.753786,-21.736249,2.508333 (Object 6)
hit at (x,y,z) -0.999902,-25.271000,10.761464
hit at (x,y,z) 14.556401,-17.129366,29.771000
hit at (x,y,z) 27.271000,-10.474983,14.233978
Ray start: alt = 44.500002, azimuth = 114.953272, Dir vector =
<-0.700909, -0.300905, 0.646670>
hit at (x,y,z) -25.627517,-11.002076,27.644355
hit at (x,y,z) -2.585912,-21.717526,2.696704
hit at (x,y,z) -2.535055,-21.902535,2.508333 (Object 4)
hit at (x,y,z) -2.488467,-22.072013,2.680891
hit at (x,y,z) -4.672186,-25.271000,6.483473
```

References

1. DOD 1990 TM-5-1300, NAVFAC P-397, AFB 88-22, Structures To Resist The Effects Of Accidental Explosions, 1990

2. LLNL 1997a Contained Firing Facility (CFF) Porthole Glass Failure - Revision 2, Draft, November 22, 1997

3. LLNL 1992 UCRL-ID-110732, Shrapnel Protection Testing In Support Of The Proposed Site 300 Contained Firing Facility, August 6, 1992

4. Viracon 1989 Security Glass Specification Guide, Viracon, Inc., 08810/VIR BuyLine 5838, 1989

5. CBPEC 1991 13070/CHI BuyLine 3155, Attack Resistant Security Systems, Chicago Bullet Proof Equipment Company, 1991

6. SRI 1993 Design And Testing Of Fragment Resistant Observation Windows, GTE Facility, Kelly AFB, Texas, Southwest Research Institute, July 1993

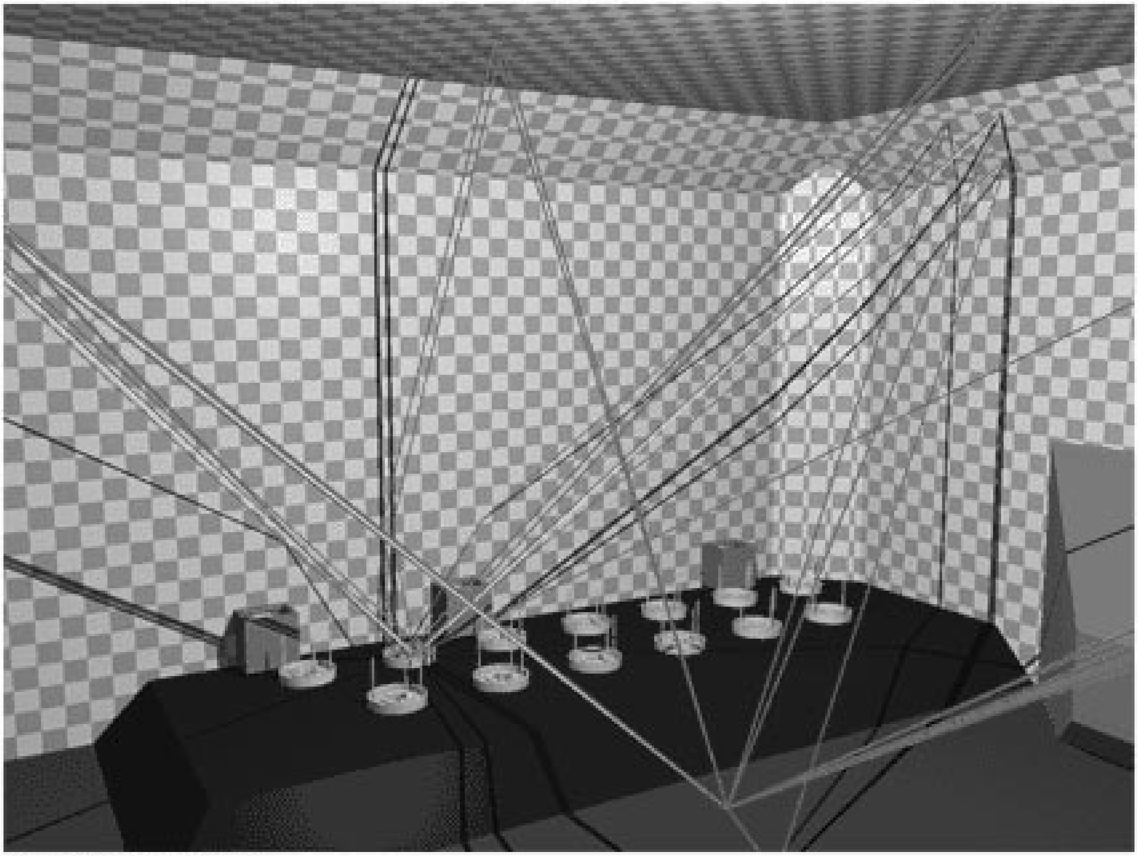

Figure 1, CFF One and Two Bounce Fragment Paths, Port 3